# ASYMMETRIC DARK MATTER AND FLAVOR

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with A. Falkowski, in preparation

# MOTIVATION

- we expect NP at TeV that couples to the SM fields
  - hierarchy problem
- if generic flavor violation: large FCNCs
  - NP has nongeneric flavor structure
  - it also cannot be completely flavor blind
  - at least broken by the SM yukawas: MFV
- how does this affect DM-visible sector interactions?
  - DM stability?

# THE "SIMPLEST" ADM

- DM either Dirac ferm. or compl. scalar
- will assume $B\neq 0$ and $L=0$ for DM
- we assume no discrete symmetry
  - operators of the form $\psi \cdot$ (SM) allowed
  - the aim of this talk:

ADM+MFV$\Rightarrow$ cosmol. stable DM

# THE "SIMPLEST" ADM

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- w
  - ... llowed
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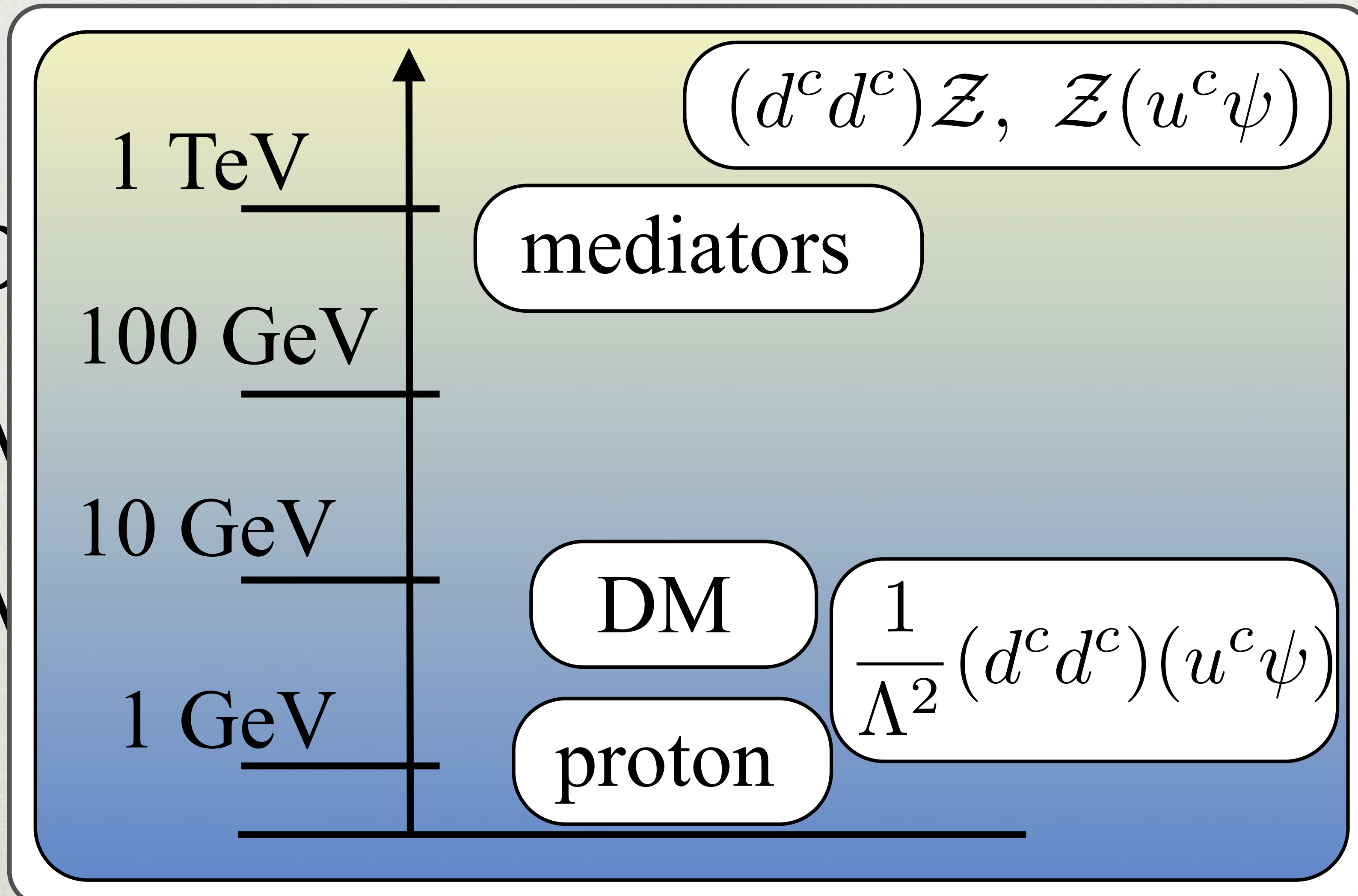


ADM+MFV⇒ cosmol. stable DM

# OUTLINE

- ADM and DM mass
- Minimal Flavor Violation
    - ADM and MFV
- implications for LHC

# ADM and DM mass

- in ADM DM mass generically *O(5-10 GeV)*
- Question: how does DM mass depend on:
  - *B* assignment of DM
  - the field content of the full model
- precise DM mass important for later discussion

# DM mass

- for simplicity assume that dark sector decouples above EW phase transition; first no new states apart from DM
- chemical equilibrium: $\mu_i = \sum_Q Q_i c_Q$

Harvey, Turner, 1990
Feldstein, Fitzpatrick, 1003.5662

- $Y$ and $B$-$L$ conserved, $Y=0$

$$m_X = 2.23 m_p \frac{\Omega_{DM}}{\Omega_B} \frac{1}{[X]^{\rm sum}_{B-L}} = 10.3\text{GeV} \frac{1}{[X]^{\rm sum}_{B-L}}$$

$$[X]^{\rm sum}_{B-L} \equiv \sum g^i_X [X^i]_{B-L}$$

$g_X^i=1(2)$ for each Weyl fermion (complex scalar) $X$ field at decoupling

- larger $B$-$L$ $\Rightarrow$ smaller DM mass
- example: $X^*(LH)^2$ asymm. operator $\Rightarrow$ $X$ complex scalar, $[X]_{B\text{-}L}=2$, $g_X=2$ $\Rightarrow$ $[X]^{\rm sum}_{B-L} = 2 \cdot 2 = 4$

# DM MASS

- how does this relation change, if additional states at decoupling?
- full expression possible, but just showing limits
- case I: NP states have *B=L=0*, but *Y≠0*

$$m_X = 10.3\text{GeV}\,\frac{1}{[X]^{\rm sum}_{B-L}}\,\frac{1+[Y^2]_{\rm NP}/7}{1+[Y^2]_{\rm NP}/11},$$

  - here NP only increases DM mass (up to 60~%)
- case II: NP states have *Y=0*, but *B,L≠0*

$$m_X = \frac{10.3\text{GeV}}{[X]^{\rm sum}_{B-L}}\Big[1+\frac{11}{28}\Big([B^2]_{\rm NP}-[BL]_{\rm NP}\Big)\Big]$$

  - if *L>B*, then DM mass can be smaller
  - if *B>L* and *B* is large, DM can be arbitrarily large
- for not extraordinarily large values of *Y*, *B*, *L*, assuming SM at decoupling is a good proxy

# ADM+MFV upshot

- we discuss models with $B \neq 0, L=0$
- for DM to be color singlet $\Rightarrow$ $B$ is integer
- will look at three cases $B$=1,2,3

| $B$ | $M_{DM}$ | $\Lambda$ |
|---|---|---|
| 1 | 5.2 GeV | $10^{11}$ GeV |
| 2 | 2.6 GeV | 100 GeV |
| 3 | 1.7 GeV | stable |

# B=1

(ADM+MFV)

# ADM with B=1

- in this case DM is a fermion
  - has mass: two Weyl fermions $\psi$, $\psi^c$ with $B$=±1
- if ADM then DM mass is 5.2 GeV
- two sets of operators that translate asymmetry from visible to dark sector

$$\text{type i)} : \frac{1}{\Lambda^2}(d^c d^c)(u^c \psi),$$
$$\text{type ii)} : \frac{1}{\Lambda^2}(q_i^* q^{i*})(d^c \psi),$$

- Lorentz structure not important for us
- for flavor structure we assume MFV

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# NEW PHYSICS FLAVOR PROBLEM

- we expect new physics at TeV
- however, if generical flavor structure:
  - generates Flavor Changing Neutral Currents
  - these FCNCs are too big, clash with observations

# ΔF=2 processes/NP puzzle

- NP contribs. to mixing (assuming (V-A)⊗(V-A) structure)

$$\mathcal{H}_{\rm eff} = \left(\frac{G_F^2 m_W^2}{8\pi^2}\left(V_{ti}^* V_{tj}\right)^2 C_0 + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}\right)\left[\bar{d}_i \gamma_\mu (1-\gamma_5) d_j\right]^2$$

- measurms. exclude O(1) corrections

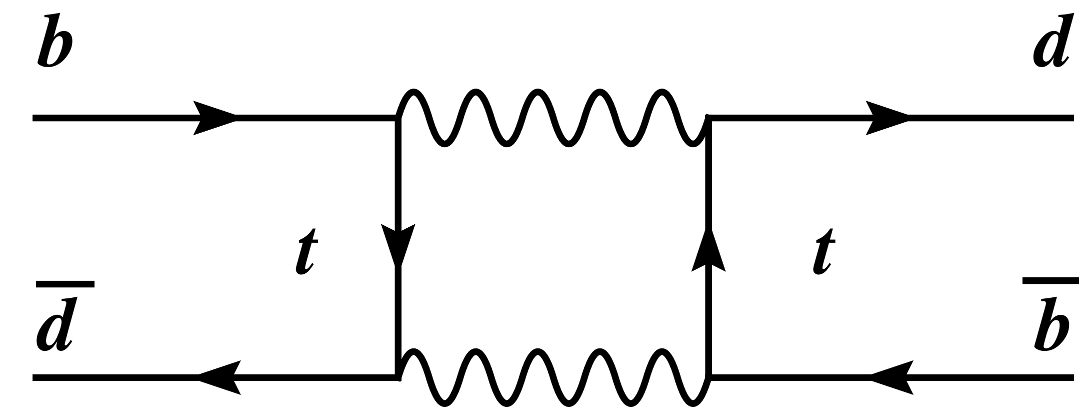
$K-\bar{K}$ mix.: $\quad (\underbrace{V_{ts}^*}_{\sim\lambda^2} \underbrace{V_{td}}_{\sim\lambda^3})^2 \frac{1}{\Lambda_{\rm MFV}^2} > \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \Rightarrow$ $\Lambda_{\rm NP} \gtrsim 10^4$ TeV

$B_d-\bar{B}_d$ mix.: $\quad (\underbrace{V_{tb}^*}_{\sim 1} \underbrace{V_{td}}_{\sim\lambda^3})^2 \frac{1}{\Lambda_{\rm MFV}^2} > \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \Rightarrow$ $\Lambda_{\rm NP} \gtrsim 5 \cdot 10^2$ TeV

$B_s-\bar{B}_s$ mix.: $\quad (\underbrace{V_{tb}^*}_{\sim 1} \underbrace{V_{ts}}_{\sim\lambda^2})^2 \frac{1}{\Lambda_{\rm MFV}^2} > \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \Rightarrow$ $\Lambda_{\rm NP} \sim 10^2$ TeV

$$\Lambda_{\rm MFV} = \sqrt{8}\pi / G_F m_W \sim 6 \text{ TeV}$$

# ΔF=2 process

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# MINIMAL FLAVOR VIOLATION

D'Ambrosio, Giudice, Isidori, Strumia, 2002
Buras et al, 2000; Chivukula, Georgi, 1987
Hall, Randall, 1990

- if NP at TeV it has a very nontrivial flavor structure
- can NP emulate the SM hierarchy?
- Minimal Flavor Violation hypothesis: flavor only broken by SM Yukawas
- a nonempty set: MSSM with gauge mediated SUSY breaking

# MINIMAL FLAVOR VIOLATION- BOOK KEEPING

D'Ambrosio, Giudice, Isidori, Strumia, 2002

- use spurion analysis to construct NP opers./contribs.
- promote Yukawas to spurions

$$Y'_{u,d} = V_Q Y_{u,d} V^\dagger_{u,d} \qquad Q' = V_Q Q \qquad u' = V_u u \qquad d' = V_d d$$

- quark sector formally inv. under $U(3)_Q \otimes U(3)_u \otimes U(3)_d$

$$u^c Y_U^\dagger q^i H_i \qquad d^c Y_D^\dagger q^i H_i^c$$

- constrains possible FV structures, e.g. $(V\text{-}A)\otimes(V\text{-}A)$
  - allowed: $\bar{Q}(Y_u Y_u^\dagger)^n Q$
  - not allowed: $\bar{Q} Y_d^\dagger (Y_u Y_u^\dagger)^n Q$
- it gives SM like suppression of FCNC's since

$$(Y_u Y_u^\dagger)^n \sim (Y_u Y_u^\dagger) = V_{\rm CKM} \mathrm{diag}(0,0,1) V^\dagger_{\rm CKM}$$

)

# ADM with B=1

- first focus on type i) operators
- to make it invar. under $G_F$ many yukawa insert. possible
- we focus on the minimal case

$$[d^c_A d^c_B][(u^c Y_U^\dagger Y_d)_C \psi]\epsilon^{ABC}$$

- Levi-Civita picks one contrib. from each generation
- possible decay $\psi \to tsd$ but down by off-shellness of top
- leading is then $\psi \to csd$, using NDA

$$\Gamma(\psi \to csd) \simeq \frac{1}{16\pi}\left|\frac{1}{\Lambda^2} y_c y_b V_{ts}\right|^2 \frac{1}{16\pi^2} m_\psi^5 =$$
$$= 2 \cdot 10^{-50}\text{GeV} \times \left(\frac{10^{10}\text{GeV}}{\Lambda}\right)^4 \left(\frac{m_\psi}{5.2\text{GeV}}\right)^5 y_b^2,$$

- compare with cosmic ray bounds $\tau > 10^{26} s$ or $\Gamma < 10^{52}$ *GeV*

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# ADM with B=1

- type ii) operators
- again focus on minimal insertion of yukawas

$$[q^*_{iA} q^*_{jB}][(d^c Y_d^\dagger)_C \psi]\epsilon^{ABC}\epsilon^{ij} \to [u^*_{LA} d^*_{LB}][(d^c Y_d^\dagger)_C \psi]\epsilon^{ABC}$$

- the leading decays are $\psi \to bcd$, $\psi \to bud$

$$\Gamma(\psi \to bcd, bus) \simeq \frac{1}{16\pi} y_b^2 \Big(\frac{1}{\Lambda^2}\frac{1}{m_W^2}\Big) m_\psi^9 \Big(\frac{1}{16\pi^2}\Big) =$$
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- for $B = 1$ ADM one needs $\Lambda > 10^{11}$ *GeV* for DM to be stable on cosmological time scales

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# B=2

## (ADM+MFV)

# ADM with B=2

- in this case DM is a complex scalar
- if ADM then DM mass is $M_X$= 2.6 GeV
  - below $b$ quark mass
  - has to decay to two nucleons (e.g. $p$ or $n$)
  - small energy release
- three sets of operators (all dim 10)

$$\text{type i)}: \quad \frac{1}{\Lambda^6}(d^c d^c)(d^c d^c)(u^c u^c)\varphi,$$

$$\text{type ii)}: \quad \frac{1}{\Lambda^6}(d^c d^c)(d^c u^c)(q^{*i} q^*_i)\varphi,$$

$$\text{type iii)}: \quad \frac{1}{\Lambda^6}(d^c d^c)(q^{*i} q^*_i)(q^{*j} q^*_j)\varphi.$$

# DOMINANT DECAY

- minimal number of yukawa insertions

$$\varphi[d^c_A d^c_B][d^c_C (d^c Y_D^\dagger Y_U)_{A'}][u^c_{B'} u^c_{C'}]\epsilon^{ABC}\epsilon^{A'B'C'} =$$
$$= \varphi d^c s^c b^c b^c y_b y_t u^c c^c + \cdots$$

- the leading decay is φ→*dsbbuc*
  - at quark level is 6-body quark decay
  - however small eng. release ⇒ cannot use OPE
  - in NDA estimate use dominance of two-body decays
  - two *b* quarks and *c* quark are off-shell: decay through weak interactions
    - prolongs decay time considerably

# DOMINANT

- minimal number of yukawa ins

$$\varphi[d^c_A d^c_B][d^c_C(d^c Y_D^\dagger Y_U)_{A'}][u^c_B$$
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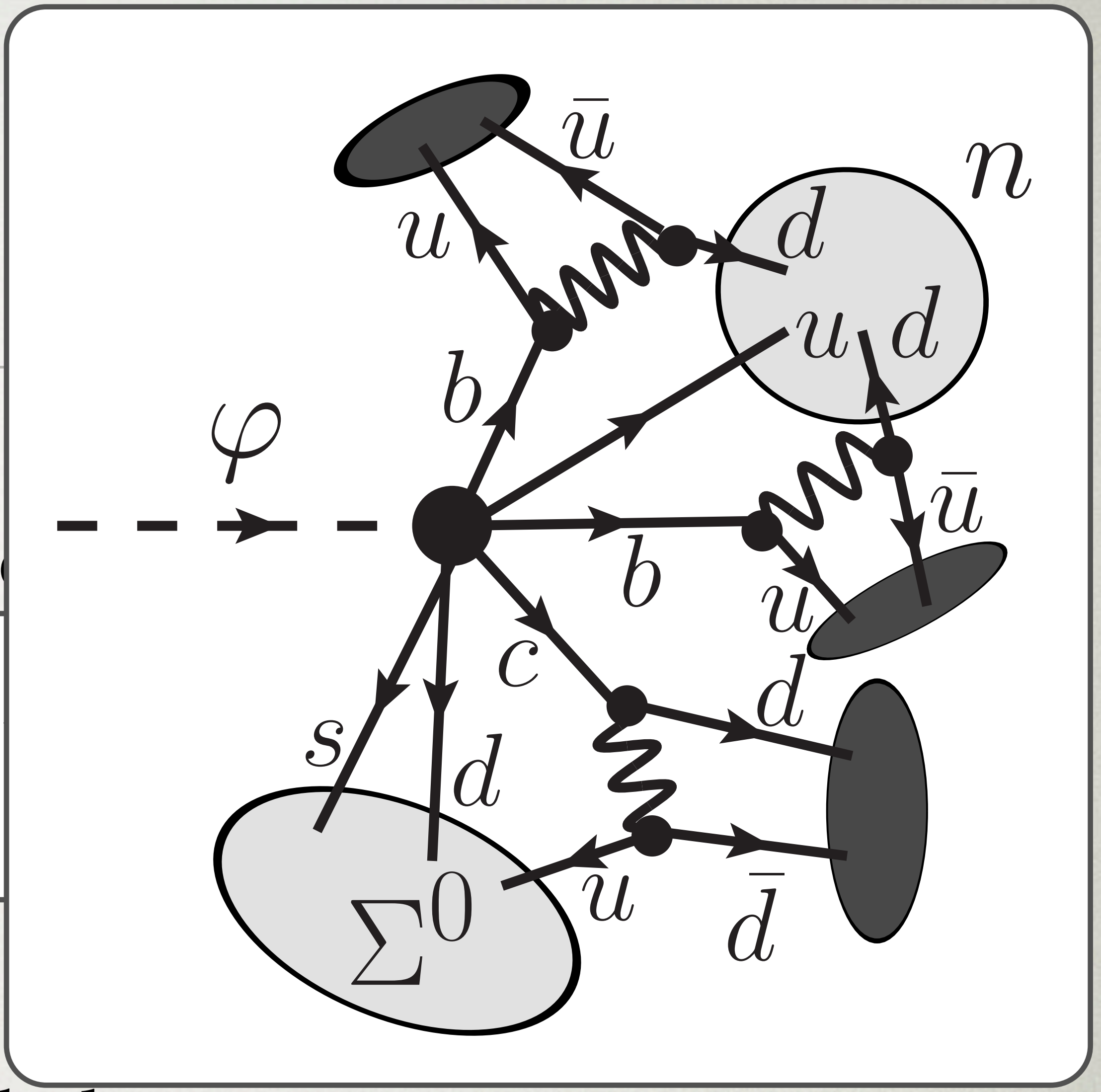


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# DOMINANT DECAY

- this gives for the dominant decay

$$\Gamma(\varphi) = \frac{1}{16\pi^2}\left[y_b \frac{1}{\Lambda^6}\left(\frac{1}{m_W^2}\right)^3 V_{ub}^2 V_{cd}\left(\frac{1}{m_b^2}\right)^2\right]^2 m_\varphi^{33} =$$
$$= 5 \cdot 10^{-58}\ \text{GeV} \times y_b^2\left(\frac{m_\varphi}{2.6\ \text{GeV}}\right)^{33}\left(\frac{300\text{GeV}}{\Lambda}\right)^{12},$$

- the other two operator types give

$$\Gamma(\varphi)^{\text{type ii)}} \simeq (y_c/y_b)^2\Gamma(\varphi)^{\text{type i)}}$$
$$\Gamma(\varphi)^{\text{type iii)}} \simeq \Gamma(\varphi)^{\text{type i)}}$$

- this means that ADM+MFV with *B=2* can have weak scale mediator masses

# WHAT DOES MFV BUY US?

- assuming generic flavor structure
  - the direct decay to only lightest quarks possible

$$\Gamma(\varphi) \simeq 10^{-26}\ \text{GeV}\left(\frac{m_\phi}{2.6\text{GeV}}\right)^{13}\left(\frac{300\ \text{GeV}}{\Lambda}\right)^{12}$$

- compare with the rate in ADM+MFV

$$\Gamma(\varphi) = \frac{1}{16\pi^2}\left[y_b \frac{1}{\Lambda^6}\left(\frac{1}{m_W^2}\right)^3 V_{ub}^2 V_{cd}\left(\frac{1}{m_b^2}\right)^2\right]^2 m_\varphi^{33} =$$
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# B=3 AND HIGHER

- for *B*=*3* and higher the DM is stable kinematically
- *B*=*3*, DM mass is 1.7 GeV
  - but has to decay to 3p,n+X

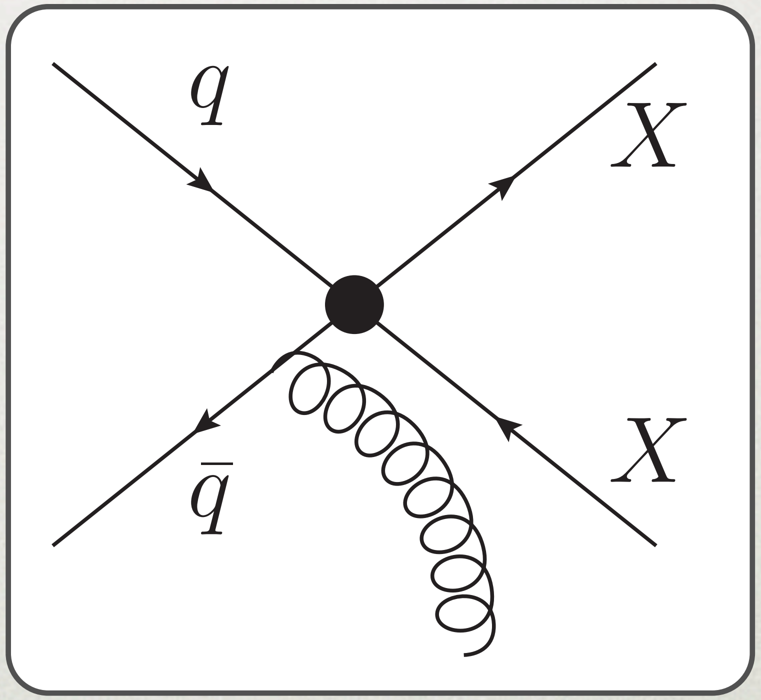
# SIGNALS AT LHC

# SIGNALS AT LHC

- for $B$=2 case the mediators can be at weak scale
  - can it be tested at LHC?
  - how to distinguish ADM (and ADM +MFV) models from thermal relic?

# PAIR PRODUCTION

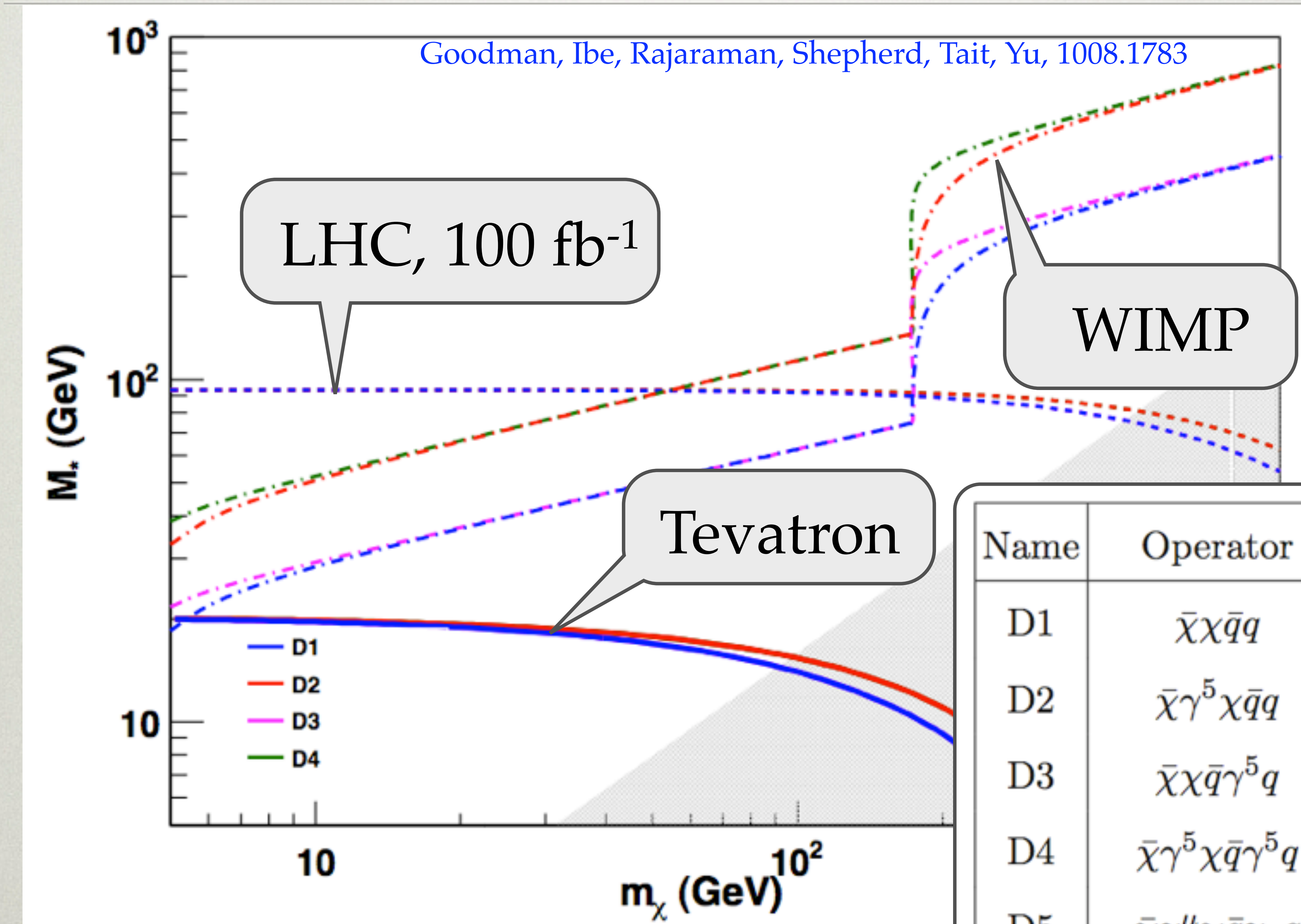
- pair production: *2DM+jet* $\Rightarrow$ *MET+jet*
  - ADM and ADM+MFV similar
  - generically larger product. cross section than WIMPs




- constraints from Tevatron

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783;1005.1286
Bai, Fox, Harnik, 1005.3797

# BOUNDS FROM TEVATRON




| Name | Operator | Coefficient |
|---|---|---|
| D1 | $\bar{\chi}\chi\bar{q}q$ | $m_q/M_*^3$ |
| D2 | $\bar{\chi}\gamma^5\chi\bar{q}q$ | $im_q/M_*^3$ |
| D3 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
| D4 | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $m_q/M_*^3$ |
| D5 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |

# PAIR PRODUCTION CONSTRAINTS

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783;1005.1286

- constraints from Tevatron, half ops. left
  - fermionic DM ; scalar DM

| | | |
|---|---|---|
| D2 | $\bar{\chi}\gamma^5\chi\bar{q}q$ | $im_q/M_*^3$ |
| D4 | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $m_q/M_*^3$ |
| D5 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D7 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |

| | | |
|---|---|---|
| C1 | $\chi^\dagger\chi\bar{q}q$ | $m_q/M_*^2$ |
| C2 | $\chi^\dagger\chi\bar{q}\gamma^5 q$ | $im_q/M_*^2$ |
| C5 | $\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/4M_*^2$ |
| C6 | $\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^2$ |

Excludable by LHC @ 100 $fb^{-1}$

- bounds avoided when light mediators

Bai, Fox, Harnik, 1005.3797

- ADM realization with light U(1)

Cohen, Phalen, Pierce, Zurek, 1005.1655

# ADM+MFV: SINGLE PRODUCTION

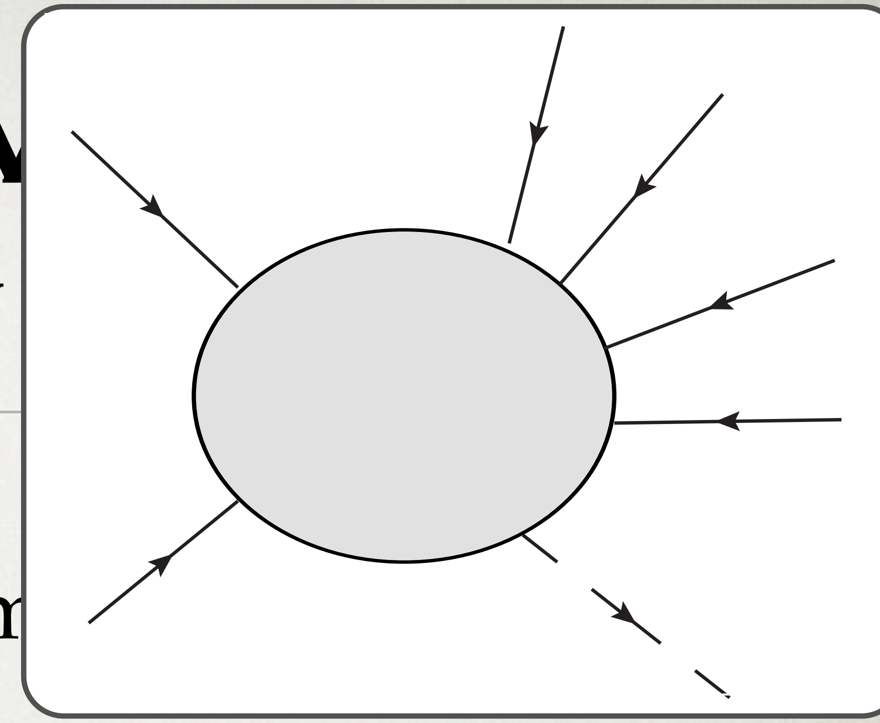
- here ADM+MFV is distinct from ADM or WIMPs
  - single DM production at LHC is possible
- focusing on $B$=2 case, type i) ops. for concreteness

$$\varphi[d^c_A d^c_B][d^c_C (d^c Y_D^\dagger Y_U)_{A'}][u^c_{B'} u^c_{C'}]\epsilon^{ABC}\epsilon^{A'B'C'} =$$
$$= \varphi d^c s^c b^c b^c y_b y_t u^c c^c + \varphi d^c s^c b^c b^c y_b y_t V_{cb} u^c t^c + h.c. \cdots ,$$

- process $du \to \bar{s}\bar{b}\bar{b}\bar{c}\varphi$ will give a signature of *2b-jets +2jets +MET*
- the second process $du \to \bar{s}\bar{b}\bar{b}\bar{t}\varphi$ is down by $V_{cb}$ but gives a distinct signature *2b-jets+top+jet+MET*

# ADM+MFV

## SINGLE PRODU



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# SINGLE PRODUCTIONS

- the EFT analysis may be just a place holder
  - determines possible signatures
- the signal will arise from on-shell states (not from production through EFT ops)
- the detailed structure will depend on the model
  - i.e. in which combs. of jets mass peaks appear
- but not which channels to search for

# A TOY MODEL

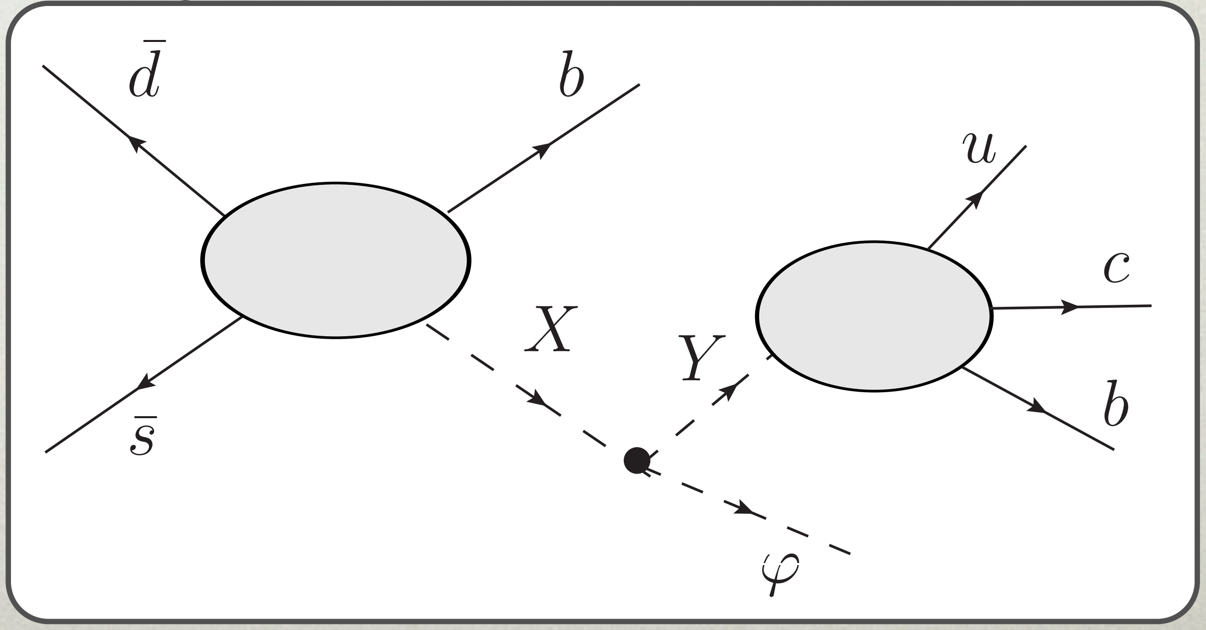
- a more explicit model for LHC signal
- add two fermion fields X and Y such that

$$(d^c d^c)(d^c X), \qquad (d^c u^c)(d^c Y)$$

- the two fermions also couple to DM

$$(X^c Y^c)\varphi$$

- one realization of the signature: $\bar{d}\bar{s} \to X b$ with $X \to Y\varphi$, and then $Y \to ucb$



# CONCLUSIONS

- showed that flavor symmetries can drastically change DM modeling
- DM in ADM+MFV with $B$=2 is stable even for weak scale mediators
- interesting signals at LHC

# BACKUP SLIDES

- annihilation has to be large (larger than for thermal relic)
- pair production though is not very distinguishing
- ADM+MFV has peculiar signatures

# AIM

- SM has $SU(3)_Q \times SU(3)_U \times SU(3)_D$ flavor group in the quark sector
  - broken by Yukawas

$$u^c Y_U^\dagger q^i H_i \qquad d^c Y_D^\dagger q^i H_i^c$$

- flavor breaking has to show up in DM-visible interactions
- is it relevant for DM↔visible sect. pheno?
  - DM stability?